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**14. ABSTRACT**
-Half-symmetric model is used in AutoDyn to simulate Depth of Penetration (DOP) experiments on SiC tile with and without a gap supported by solid Aluminum (Al5083)
-Impacts by .30cal AP M2 projectile and are modeled using SPH elements in AutoDyn
-Center strike model validation runs with SiC tiles are conducted based on the DOP experiments described in reference - ARL-TR-2219, 2000
-Tile gap is found to increase the DOP as compared to baseline center impact
-Simulations were run on gap sizes 0.508 (20 mil) and 1.061 mm (40 mil) at the standard muzzle speed of 850 m/s
-DOP is the main measurement used to determine which geometry and configuration yield the best results.

**15. SUBJECT TERMS**
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# MODELING AND SIMULATION OF CERAMIC ARRAYS TO IMPROVE BALLISTIC PERFORMANCE

# OBJECTIVE AND GOALS

- The University of Delaware Center for Composite Materials (UD-CCM) is developing the next generation of lightweight hybrid ceramic/composite armor kits for Marine Corps tactical and combat vehicles
- The focus is on simulating and modeling the performance of ceramic/composite lightweight armor at seams and corners, and improving the armor's performance in these regions

# OBJECTIVE AND GOALS

- The ceramic/composite armor is comprised of composite backings, adhesives, ceramics and covers
- The tiles will be restricted to the sintered ceramics (SiC) due to the ability to fabricate SiC into complex geometries and cost analysis conducted in previous research
- Model ballistic experiments will validate the modeling done in simulation

# SUMMARY

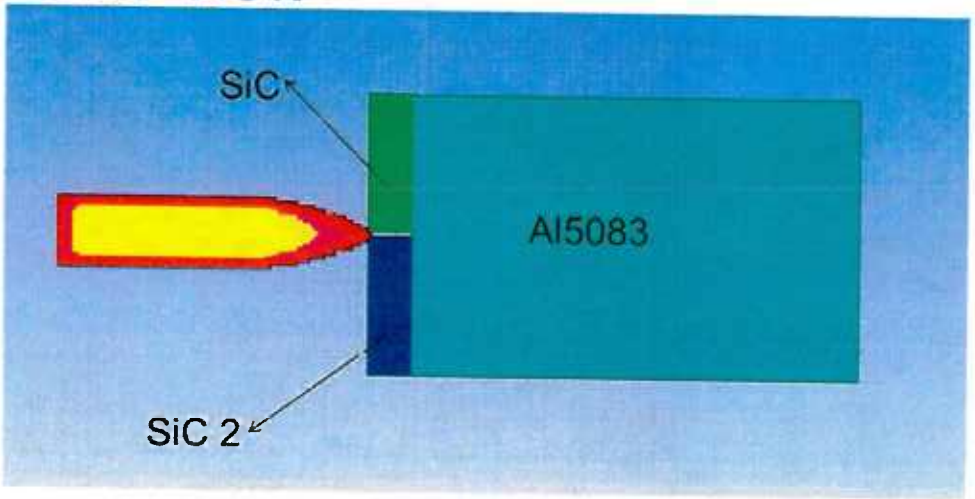
- Half-symmetric model is used in AutoDyn to simulate Depth of Penetration (DOP) experiments on SiC tile with and without a gap supported by solid Aluminum (Al5083)
- Impacts by .30cal AP M2 projectile and are modeled using SPH elements in AutoDyn
- Center strike model validation runs with SiC tiles are conducted based on the DOP experiments described in reference - ARL-TR-2219, 2000

# SUMMARY

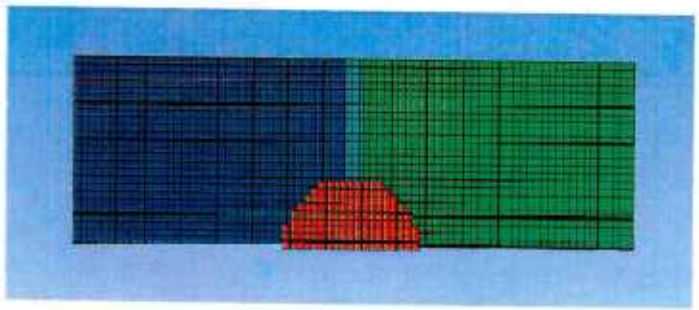
- Tile gap is found to increase the DOP as compared to baseline center impact
- Simulations were run on gap sizes 0.508 (20 mil) and 1.061 mm (40 mil) at the standard muzzle speed of 850 m/s
- DOP is the main measurement used to determine which geometry and configuration yield the best results.

# HALF SYMMETRIC MODEL WITH GAP IN AUTODYN

Side View




Front View



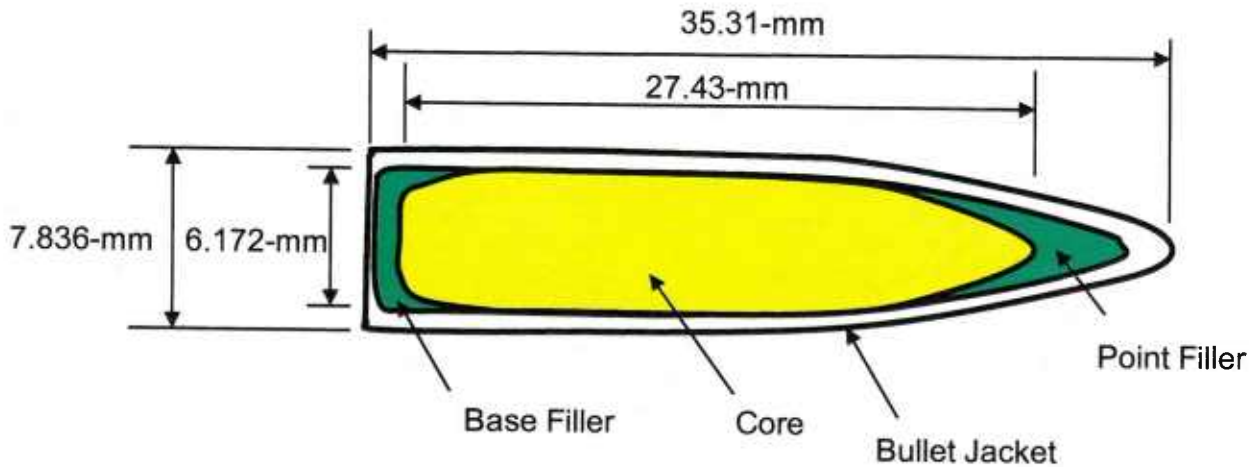
- Smoothed-particle hydrodynamics (SPH) used for all parts
- SiC and SiC 2 are identical in properties and dimensions
  - Setup as different to differentiate damage in each tile
- SPH size = 0.40-mm
- Clamp boundary condition used

# MATERIAL MODELS

## Material Models

| MATERIAL | EOS | STRENGTH MODEL | FAILURE MODEL |
|---|---|---|---|
| Steel Core | Polynomial | Johnson & Cook | Johnson & Cook |
| Lead Filler | Gruneisen | Piecewise Johnson & Cook | N/A |
| Copper Jacket | Linear | Piecewise Johnson & Cook | N/A |
| SiC Ceramic | Polynomial | JH-2 | JH-2 |
| Aluminum | Polynomial | Johnson & Cook | Johnson & Cook |
| S-Glass/Phenolic | Linear | LS-DYNA MAT162 | LS-DYNA MAT162 |
| Polymeric Foam | Linear | Non-linear Elastic | N/A |
| Adhesives & Interlayers | N/A | Cohesive Laws | Cohesive Laws |

# .30cal AP-M2 PROJECTILE MASS PROPERTIES

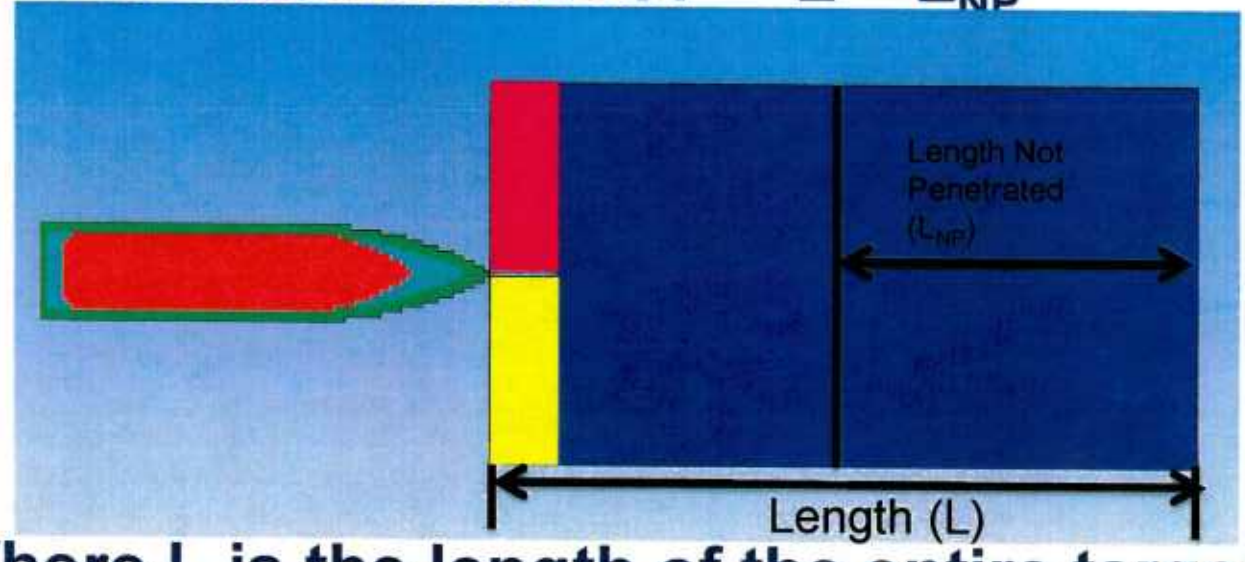



| Component | Material | Weight (g) |
|---|---|---|
| Jacket | Gilding Metal | 4.2 |
| Core | Hardened Steel - RC 63 | 5.3 |
| Point Filler | Lead | 0.8 |
| Base Filler | Lead | 0.5 |
| **Total Weight** | | **10.8** |

# DOP SIMULATION DETAILS

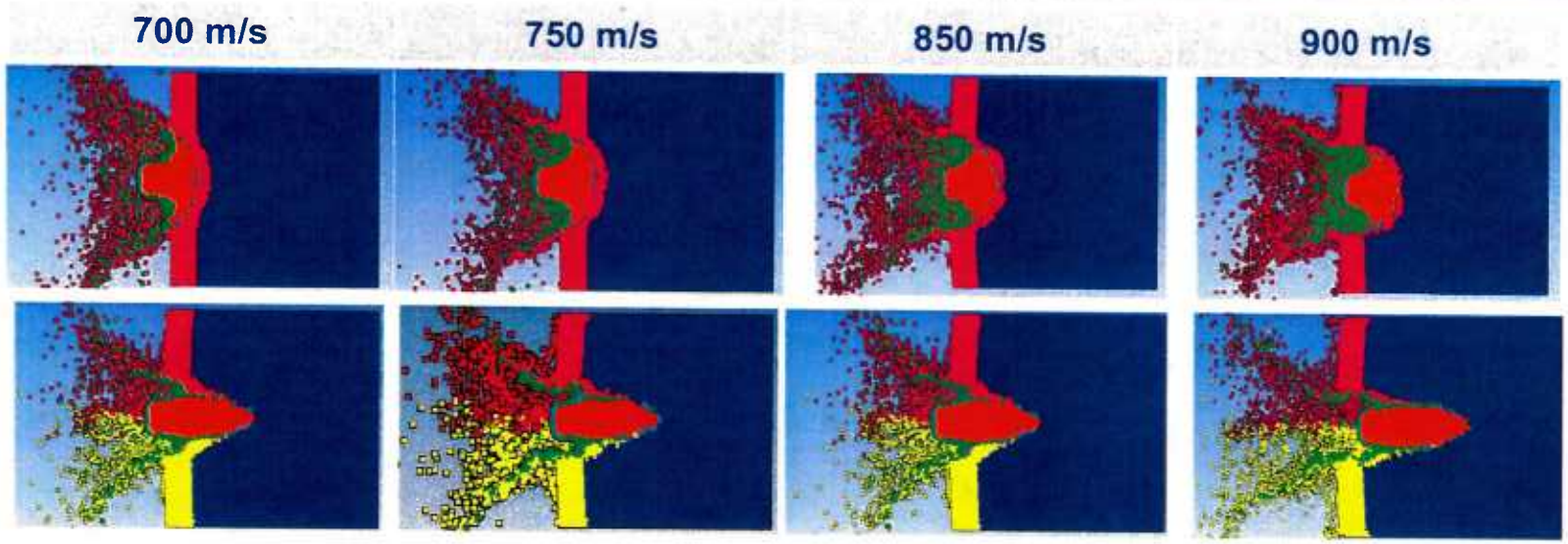
# CALCULATING DEPTH OF PENETRATION

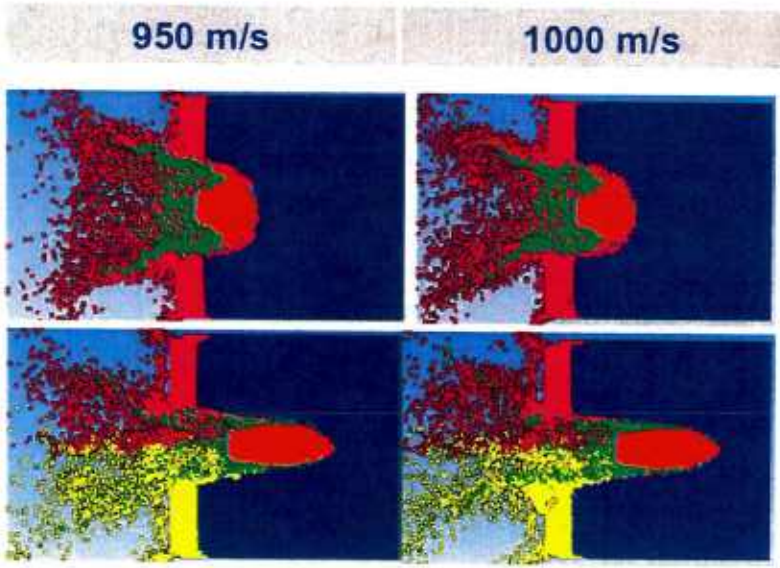
- DOP is calculated: $DOP = L - L_{NP}$




- Where L is the length of the entire target ceramic tiles and aluminum backing
- $L_{NP}$ is the length of the target left not penetrated when the velocity and kinetic energy of the projectile have reached zero

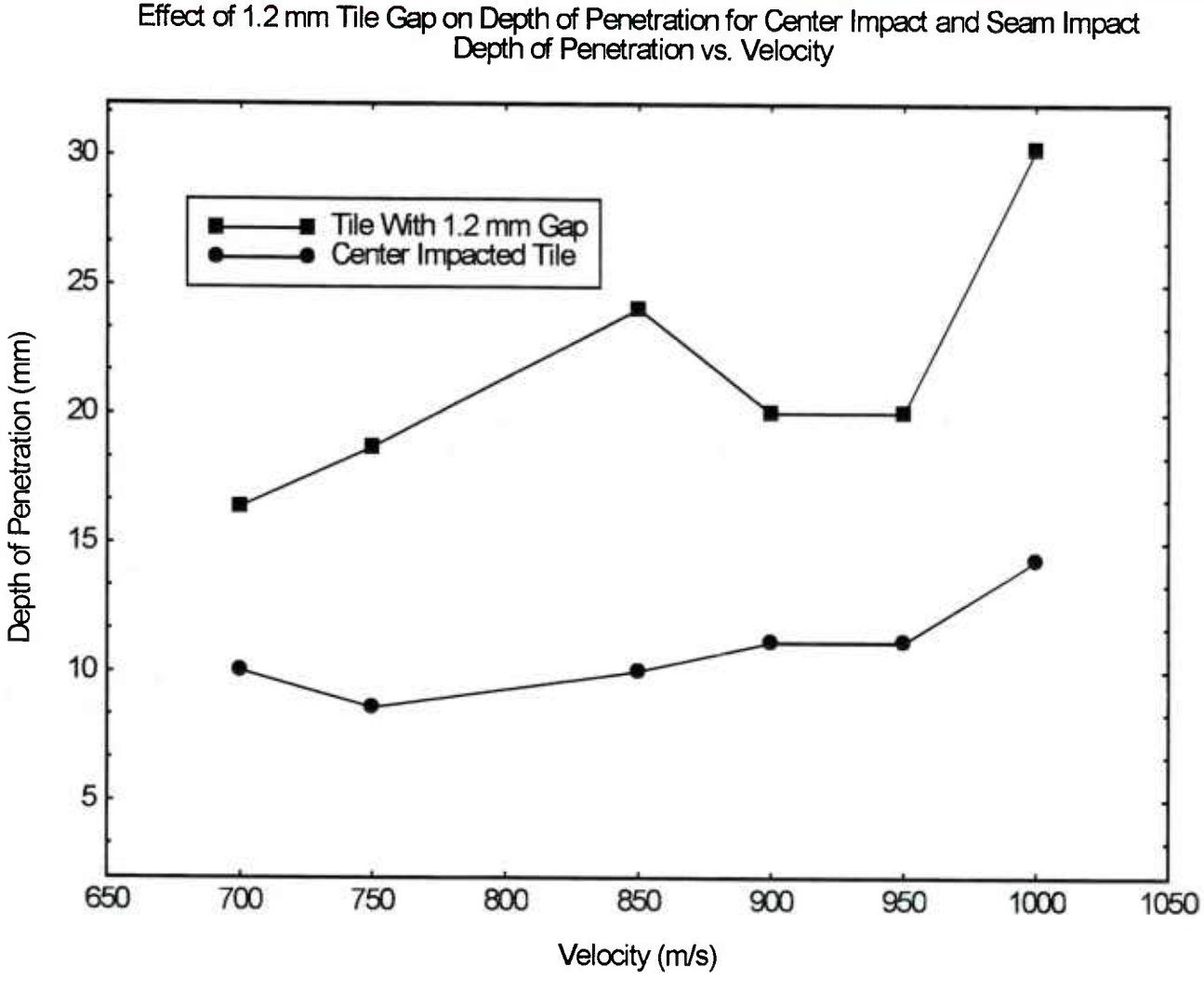
# EFFECT OF 1.2 mm TILE GAP ON DOP




| Velocity (m/s) | Center Hit Tile DOP (mm) | Tile w/ 1.2 mm Gap DOP (mm) |
|---|---|---|
| 700 | 10.02 | 16.40 |
| 750 | 8.59 | 18.70 |
| 850 | 10.00 | 24.05 |
| 900 | 11.13 | 20.04 |
| 950 | 12.96 | 28 |
| 1000 | 14.31 | 30.28 |

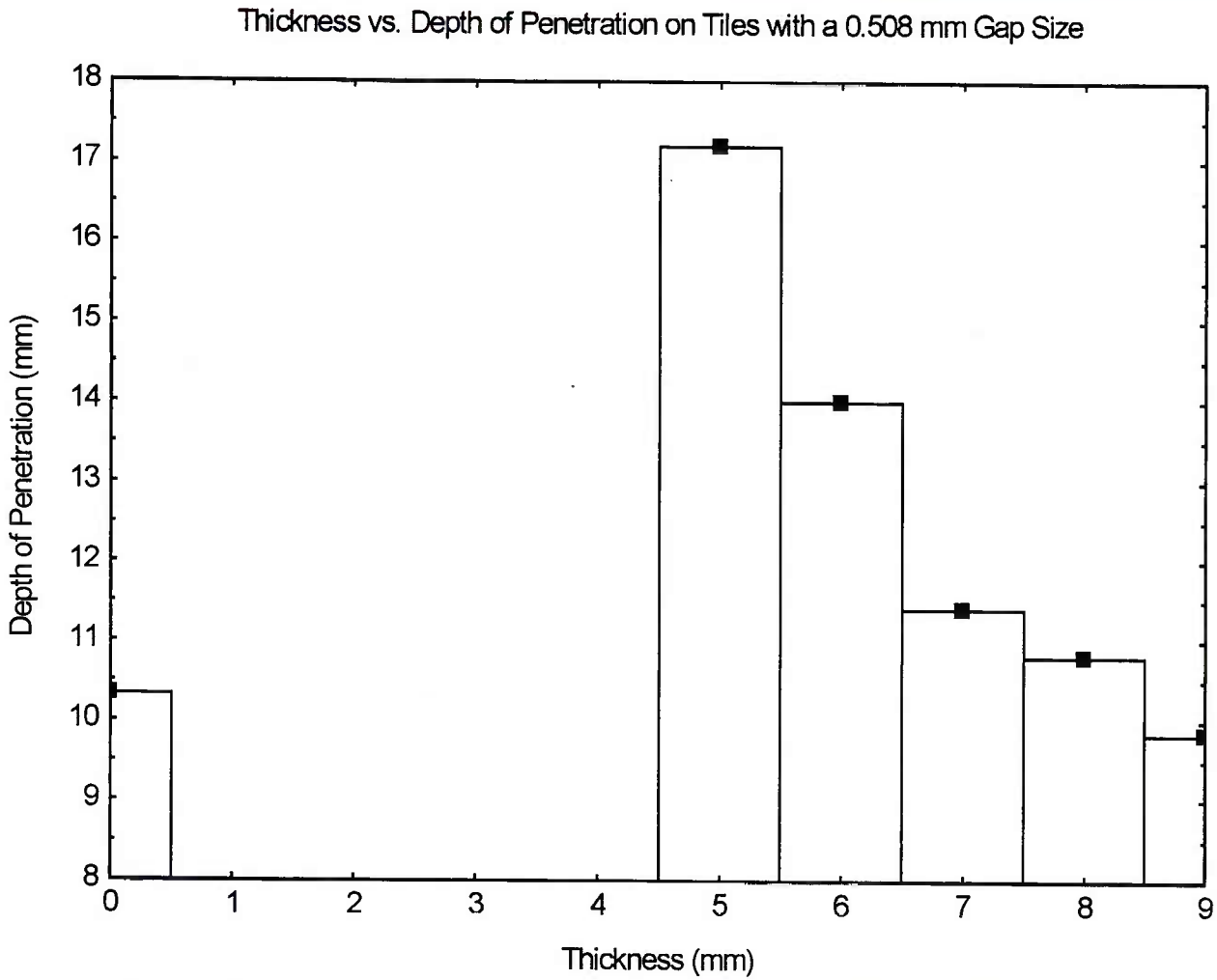
# GRAPH OF EFFECT OF A 1.2 mm TILE GAP ON DEPTH OF PENETRATION FOR CENTER IMPACT AND SEAM IMPACTED TILES



# EFFECT OF DOP ON VARYING TILE THICKNESSES AT 850 m/s GAP SIZE 0.508 mm

| Depth of Penetration on Baseline Tiles and Modified Tiles at 850 m/s, Gap Size 0.508 mm | | |
|---|---|---|
| **Gap Size (mm)** | **Tile Modification** | **Depth of Penetration (mm)** |
| None (0) | Baseline (5 mm) | 10.33 |
| 0.508 | Baseline (5 mm) | 17.19 |
| 0.508 | 6 mm | 14.00 |
| 0.508 | 7 mm | 11.40 |
| 0.508 | 8 mm | 10.80 |
| 0.508 | 9 mm | 9.83 |

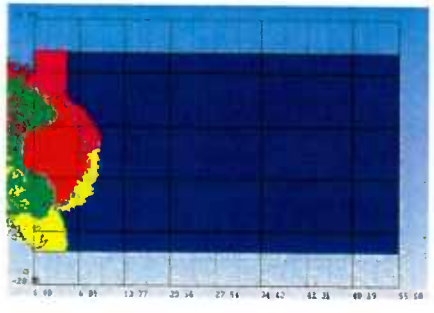
# THICKNESS VS. DEPTH OF PENETRATION ON TILES WITH A 0.508 GAP SIZE



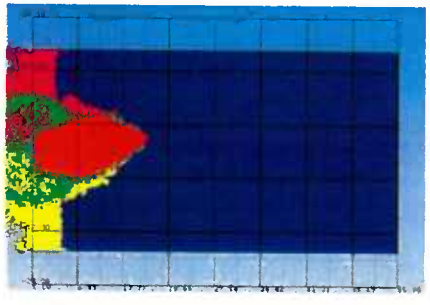

* 0 mm thickness represents Center Impacted Tile, No Gap

# EFFECT OF TILE THICKNESS ON DOP AT 850 m/s GAP SIZE 0.508 mm

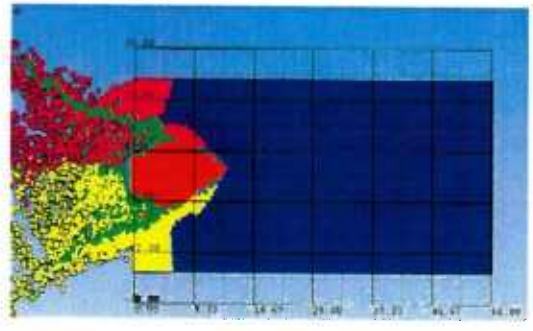
No Gap, DOP 10.33 mm



5 mm Thick, DOP 17.19 mm

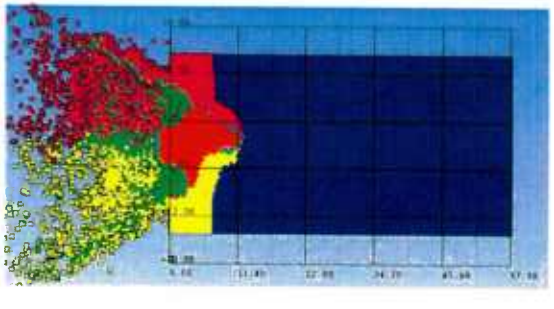


6 mm Thick, DOP 14.00 mm

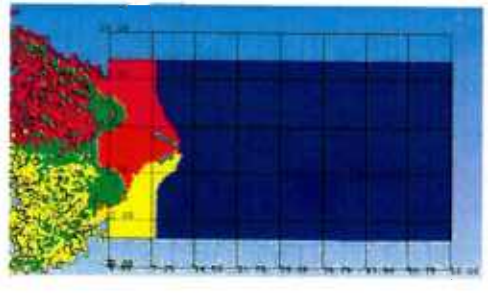


| Depth of Penetration on Baseline Tiles and Modified Tiles at 850 m/s, Gap Size 0.508 mm | | |
|---|---|---|
| Gap Size (mm) | Tile Modification | Depth of Penetration (mm) |
| None (0) | Baseline (5 mm) | 10.33 |
| 0.508 | Baseline (5 mm) | 17.19 |
| 0.508 | 6 mm | 14.00 |
| 0.508 | 7 mm | 11.40 |
| 0.508 | 8 mm | 10.80 |
| 0.508 | 9 mm | 9.83 |

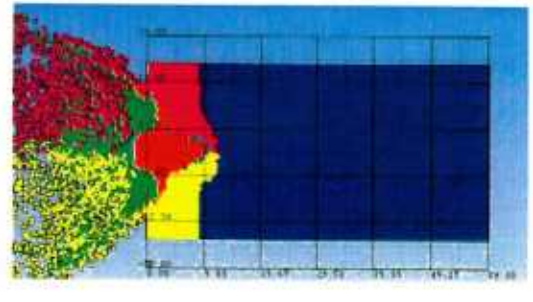
7 mm Thick, DOP 11.40 mm



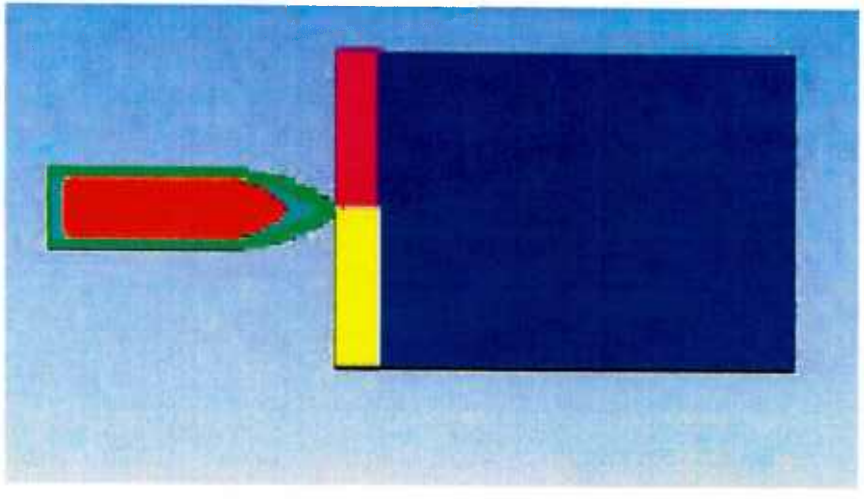
8 mm Thick, DOP 10.80 mm

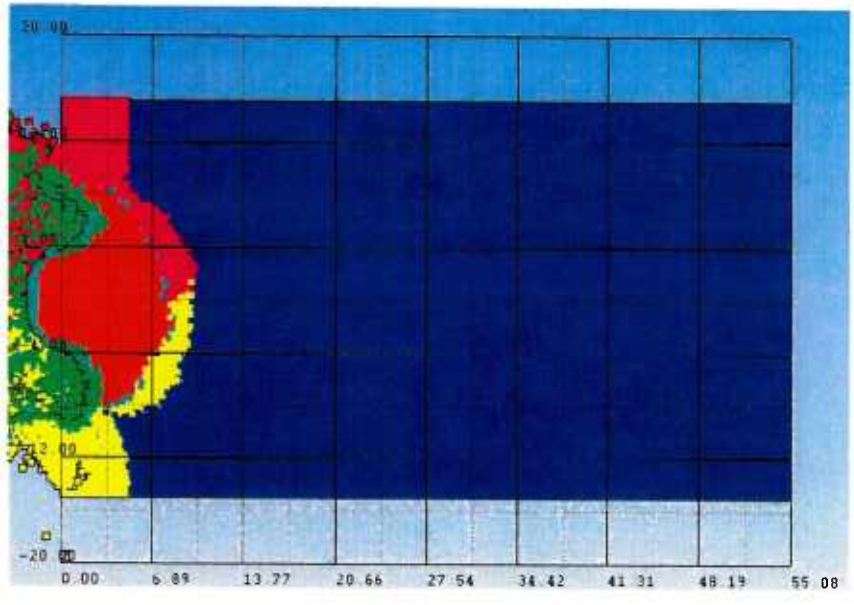


9 mm Thick, DOP 9.83 mm



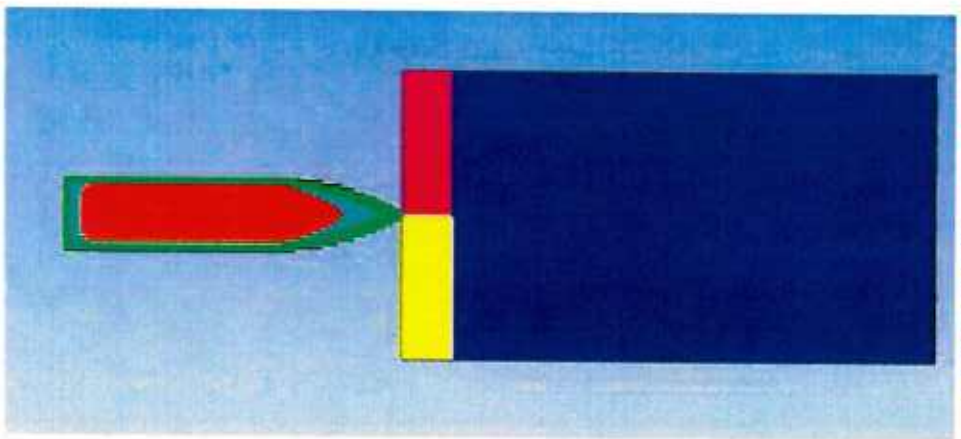
# DOP OF TWO TILES NO GAP AT 850 m/s

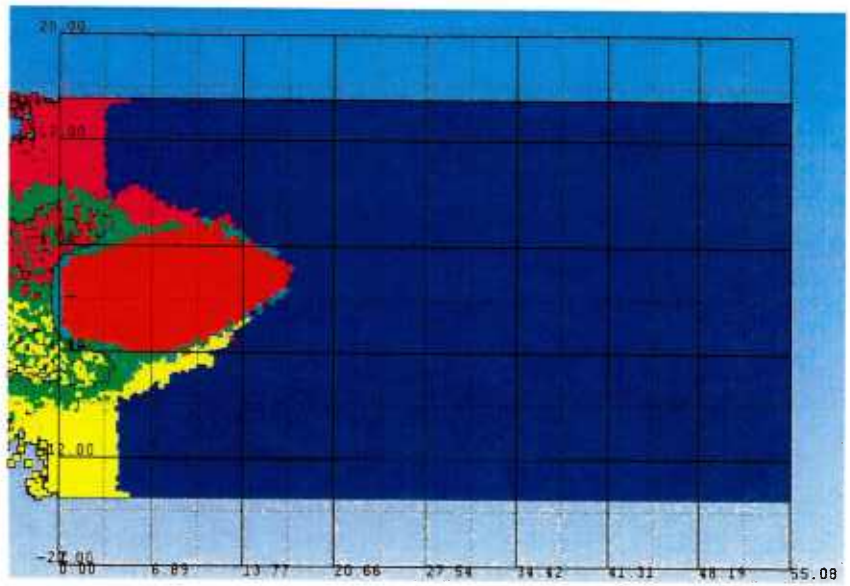




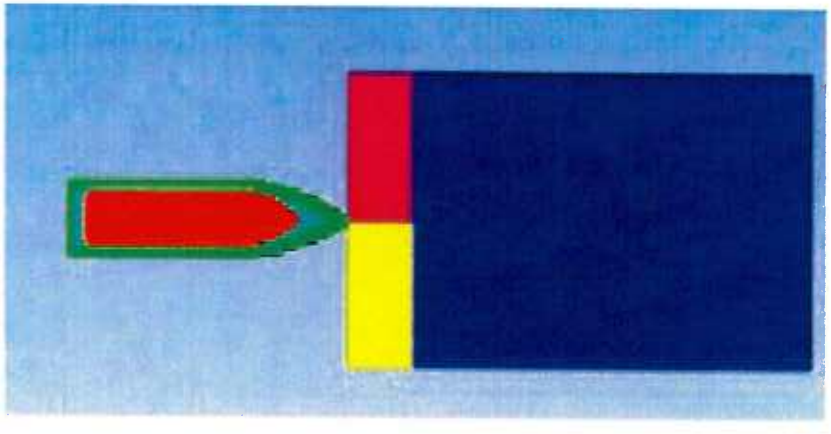

- Two tiles with no gap replicates the DOP of one solid tile

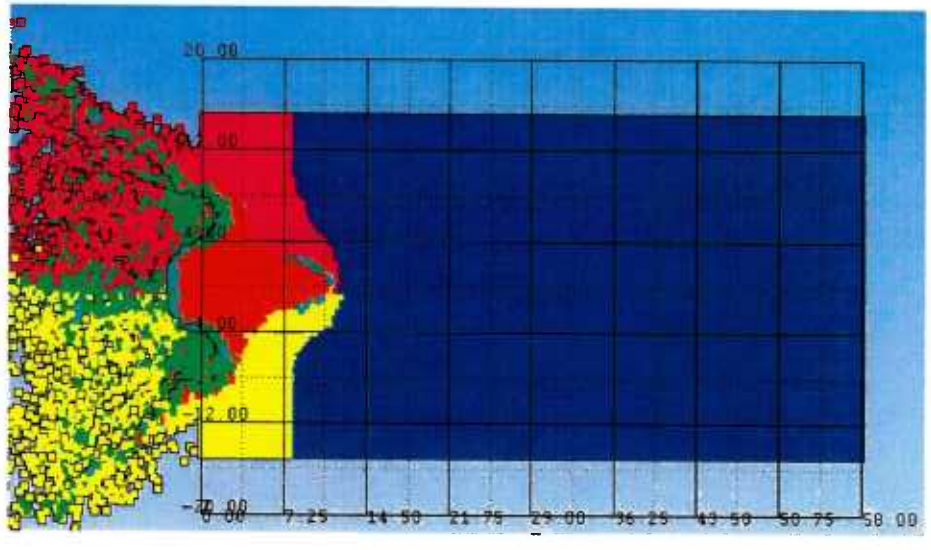
# DOP ON TWO TILES GAP SIZE 0.508
# 5 mm THICK TILE AT 850 m/s





# DOP ON TWO TILES GAP SIZE 0.508
# 8 mm THICK TILE AT 850 m/s





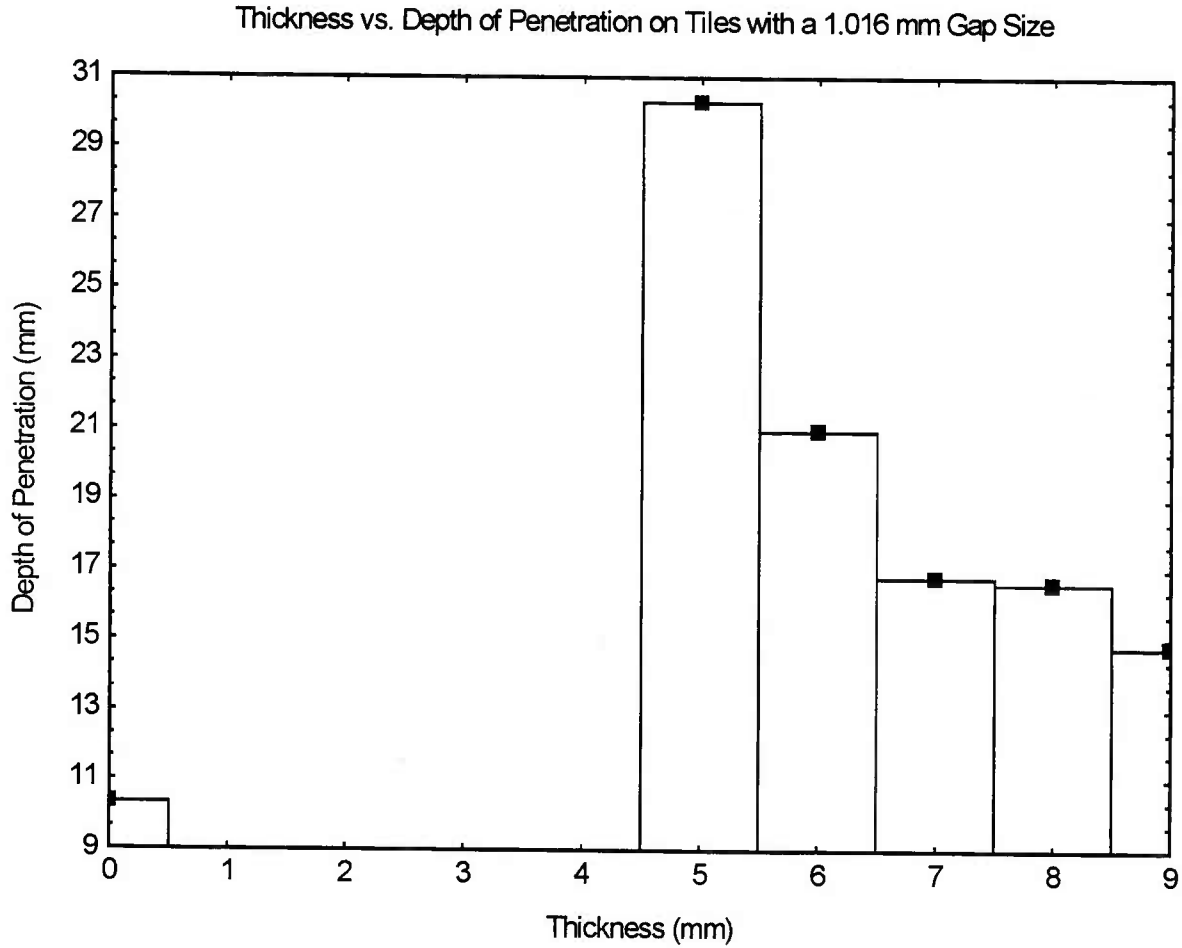
# SUMMARY OF GAP SIZE 0.508 mm RESULTS

- Achieving a DOP that was similar and even improved upon the DOP of a center impacted target was seen
- To achieve that comparable DOP the tile thickness needed to be increased by 60%
- At the gap size of 0.508 mm this is not an ideal solution, this will lower the weight and cost efficiency of the ceramic armor array

# EFFECT OF DOP ON VARYING TILE THICKNESSES AT 850 m/s GAP SIZE 1.016 mm

| Depth of Penetration on Baseline Tiles and Modified Tiles at 850 m/s, Gap Size 1.061 mm | | |
|---|---|---|
| **Gap Size (mm)** | **Tile Modification** | **Depth of Penetration (mm)** |
| None (0) | Baseline (5 mm) | 10.33 |
| 1.016 | Baseline (5 mm) | 30.29 |
| 1.016 | 6 mm | 20.95 |
| 1.016 | 7 mm | 16.76 |
| 1.016 | 8 mm | 16.59 |
| 1.016 | 9 mm | 14.77 |

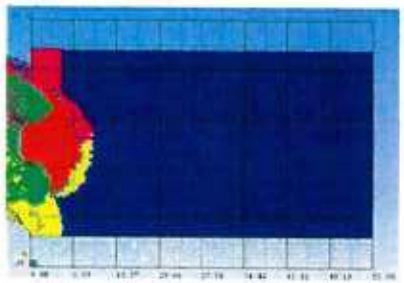
# THICKNESS VS. DEPTH OF PENETRATION ON TILES WITH A 1.016 mm GAP SIZE



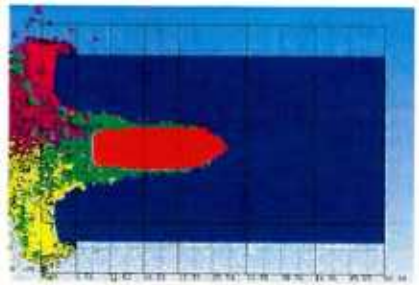

* 0 mm thickness represents Center Impacted Tile, No Gap

# EFFECT OF TILE THICKNESS ON DOP AT 850 m/s GAP SIZE 1.016 mm

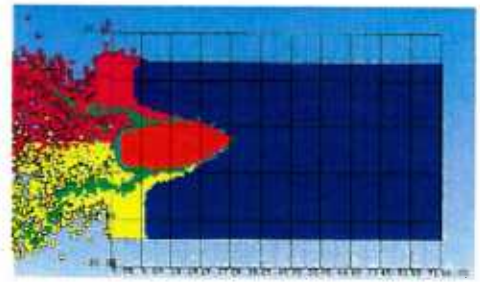
No Gap, DOP 10.33 mm



5 mm Thick, DOP 30.29 mm

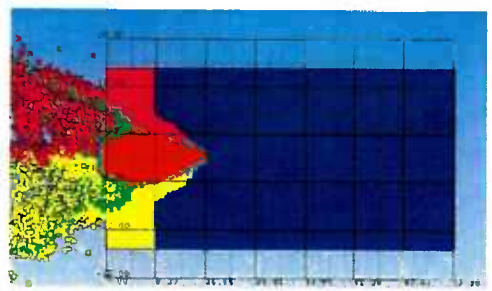


6 mm Thick, DOP 20.95 mm

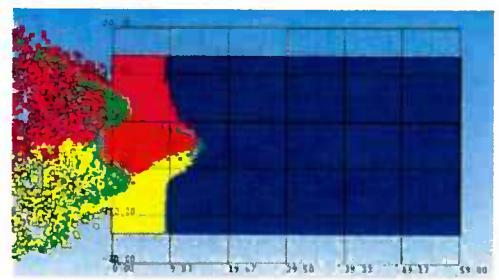


7 mm Thick, DOP 16.76 mm

8 mm Thick, DOP 16.59 mm



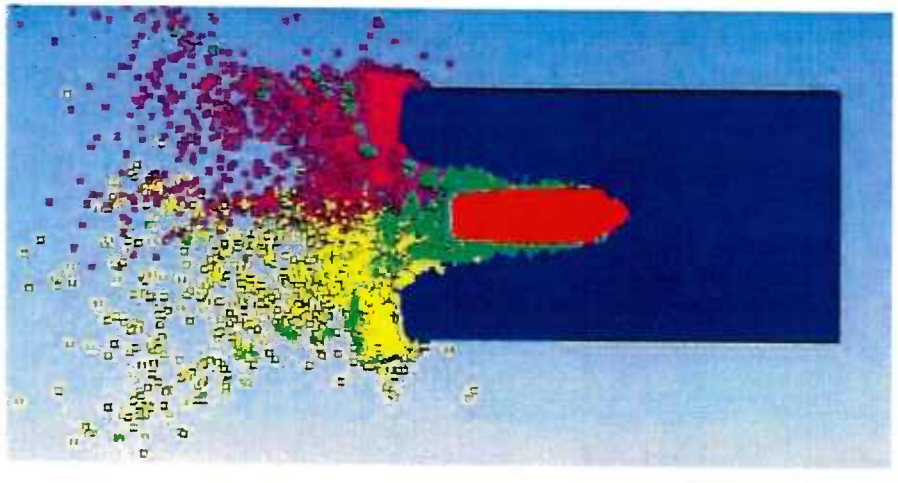
9 mm Thick, DOP 14.77 mm

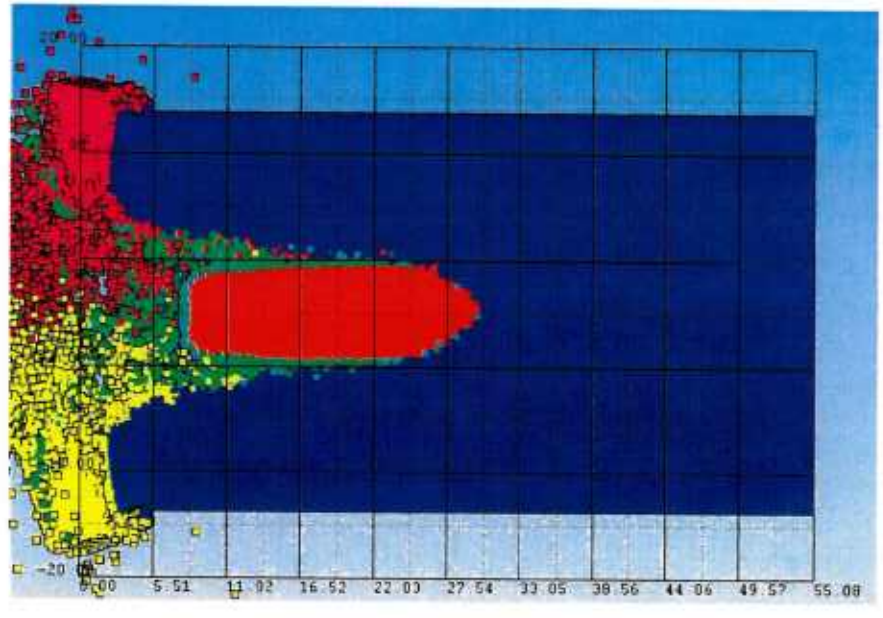


**Depth of Penetration on Baseline Tiles and Modified Tiles at 850 m/s, Gap Size 1.061 mm**

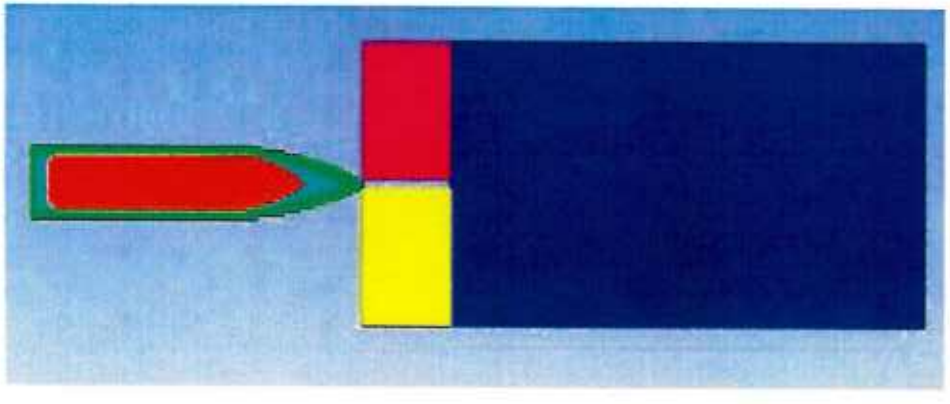
| Gap Size (mm) | Tile Modification | Depth of Penetration (mm) |
|---|---|---|
| None (0) | Baseline (5 mm) | 10.33 |
| 1.016 | Baseline (5 mm) | 30.29 |
| 1.016 | 6 mm | 20.95 |
| 1.016 | 7 mm | 16.76 |
| 1.016 | 8 mm | 16.59 |
| 1.016 | 9 mm | 14.77 |

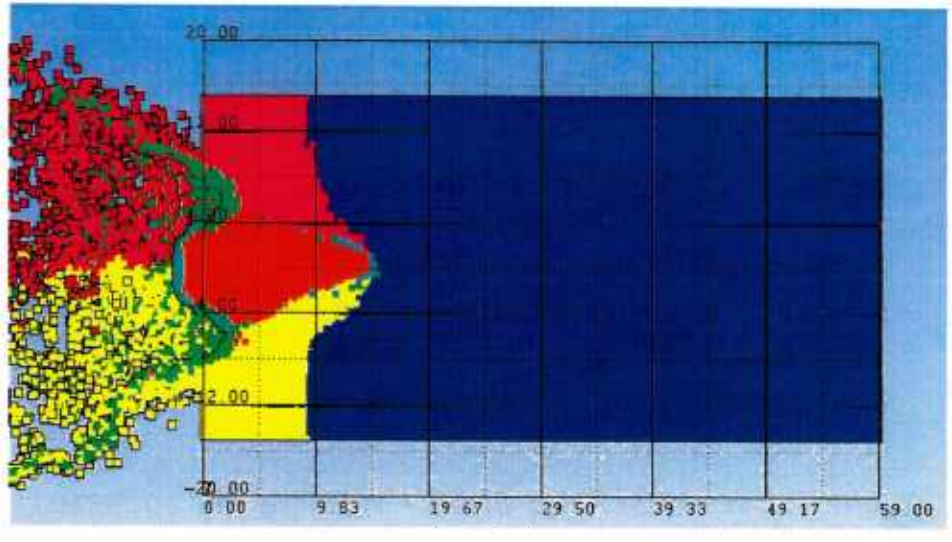
# DOP ON TWO TILES GAP SIZE 1.016
# 5 mm THICK TILE AT 850 m/s





# DOP ON TWO TILES GAP SIZE 1.016
# 9 mm THICK TILE AT 850 m/s



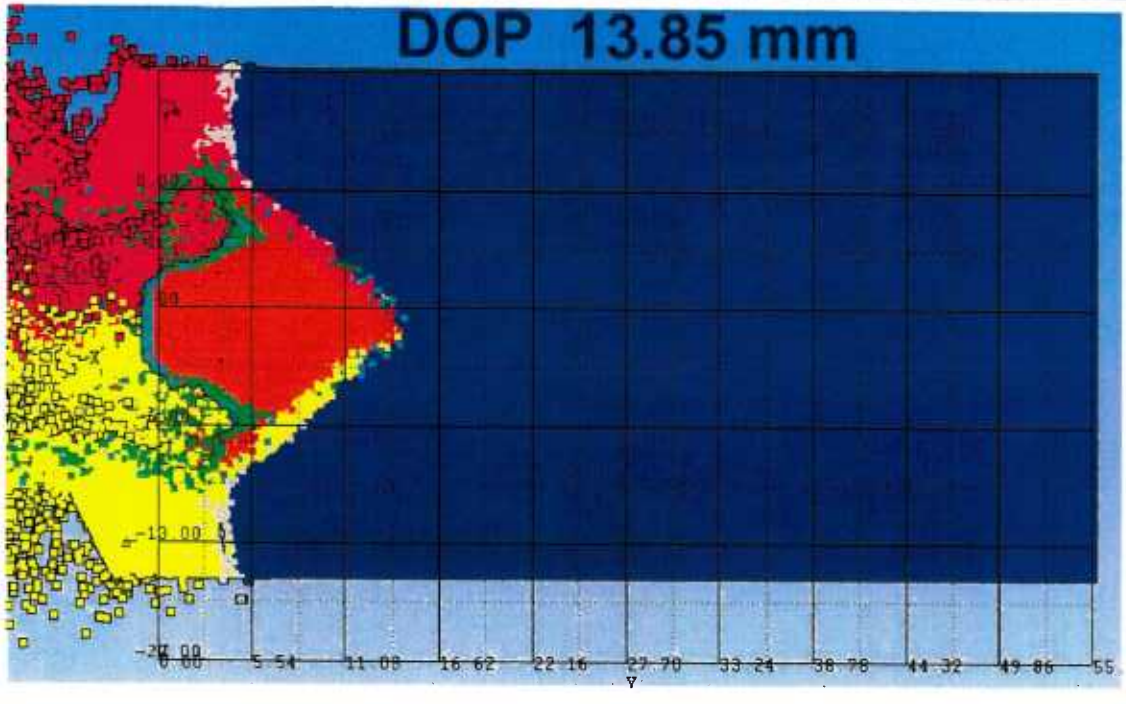


# SUMMARY OF GAP SIZE 1.016 mm RESULTS

- To achieve a DOP similar to the DOP of a center impacted tile the thickness of the tile would need to be more then doubled

- At a gap size of 1.016 mm this is not a viable option as this would give rise to cost and weight inefficient armor

# ADHESIVE LAYER GAP SIZE 0.508 mm 5 mm THICK TILE




| Adhesive Layer DOP Compared to No Adhesive Layer DOP | |
|---|---|
| **Adhesive Layer DOP (mm)** | **No Adhesive Layer DOP (mm)** |
| 13.85 | 17.19 |

- An adhesive layer of Epoxy Resin was added in between the SiC tile and the Al backing
- The tile remained 5 mm thick and the gap size at 0.508 mm to compare to the baseline results when no adhesive was added

# DISCUSSION

- Increased tile thickness at seams is one solution for increasing seam performance during projectile impacts
- Other proposed seam solutions are step ladder seams, angled seams, reducing gap size, and cover plates
- Continued modeling and experimental tests will down select for the best solution and improvement to seam design